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HF Propagation Analysis: Puerto Rico Airborne Ionospheric Observatory Flights in Support of the Over-the-Horizon Radar System

Gary S. Sales
James G. Moore
David F. Kitrosser

University of Lowell
Center for Atmospheric Research
450 Aiken Street
Lowell, MA 01854

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Flights in the coverage area of Segment 3 of the East Coast OTH-B Radar to calibrate a radar target emulator were used to study propagation conditions over long paths (> 3000 km) off the East Coast of the U.S. Analysis of MOF data, derived from oblique propagation ionograms, and MUF data derived for respective distances from the onboard ionosonde data indicate substantial discrepancies. This is, in view of the long path, not surprising. MOF changes were out of phase with path length changes. The analysis of Martyn's Theorem shows, that for the long propagation path, the contribution of MUF variation from the time dependence of foF2 was 22 times greater than the range contribution, and of the opposite sign, under the conditions observed during the measurement.

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1.0 INTRODUCTION

In early December 1987, the AFGL Airborne Ionospheric Observatory (AIO) was used as a dedicated target in the testing program of the Over-The-Horizon (OTH-B) East Coast Radar System (ECRS). The primary goal of the test flights was the calibration of the SRI, International (SRII) target emulator located at Borinquen, Puerto Rico. A second goal was the collection of an ionospheric propagation data base suitable for the further development of analysis procedures to test and evaluate the performance of Environmental Assessment software and radar frequency management procedures. This latter goal is the subject of this preliminary report.

The full analysis of these data requires considerable supporting data from the ECRS, including the coordinate registration tables and backscatter ionograms. These backscatter ionograms are the fundamental tools for radar frequency management. Unfortunately, few of these data were collected at the radar and are not included in the analysis for this interim report.

Still, it is felt that insight can be derived from the analysis presented that can be applied to future data collection and analyses during the flight test program as well as lead to the improved understanding of the radar's performance. In the future full coordination between the radar operations, the radar data collection and the airborne experiments will be planned and executed by providing written test plans.

The aforementioned goals were accomplished by flying two sorties with the AIO at ground ranges from the radar site varying from 2300 to some 3300 kilometers. These sorties were flown out of the Roosevelt Roads Naval Air Station in Puerto Rico on 2 December 1987 (87-336) and 4 December 1987 (87-338). The geographic position of the AIO during these flights was determined by recording the relevant parameters from the onboard Inertial Navigation System (INS).

The flight tracks were designed to place the AIO in Beam 6 of the OTH-B Segment 3 coverage area. Figure 1 shows the relationship between the radar beam coverage and the flight path region of the AIO in the vicinity of Puerto Rico. Figure 2 shows the range variations of the aircraft from the ECRS operations center located at Bangor, ME. The flight on 87-336 lasted for 6 hours from 1430 UT to 2030 UT, essentially a daytime flight. Aircraft takeoffs and landings were all in Puerto Rico.

The flight track for 4 December was again designed to place the AIO in Beam 6 of the OTH-B Segment 3 coverage area. Figure 3 shows the distance between the aircraft and the radar as a function of time (1315 UT to 1945 UT) for the flight on 87-338. The data from the INS system was again used to determine the range variations.

Vertical incidence ionograms, using the onboard Digisonde, and oblique ionograms, using the backscatter sounder transmissions at the OTH-B radar site and the onboard "chirp" receiver, were made at the AIO during the entire flight. These oblique ionograms have been scaled for the Maximum Observed Frequency (MOF) and the state of the ionosphere and propagation conditions during the OTH-B radar operations have been determined. The geomagnetic activity level was quiet on both flight days with a small increase in K_p at the end of the flight on Day 87-338.

In addition to these data gathered aboard the AIO, supporting data consisting of the vertical incidence ionograms from Wallops Island, VA and Millstone Hill, MA were also collected. These data, particularly Wallops Island, as the closest station to the path midpoint, serves as the source for the prediction of the MUF for the radar to the region north of Puerto Rico. A comparison is made between the MUF based on the near midpath Wallops Island sounding data and the MUF based on the near endpoint Millstone Hill sounding data.

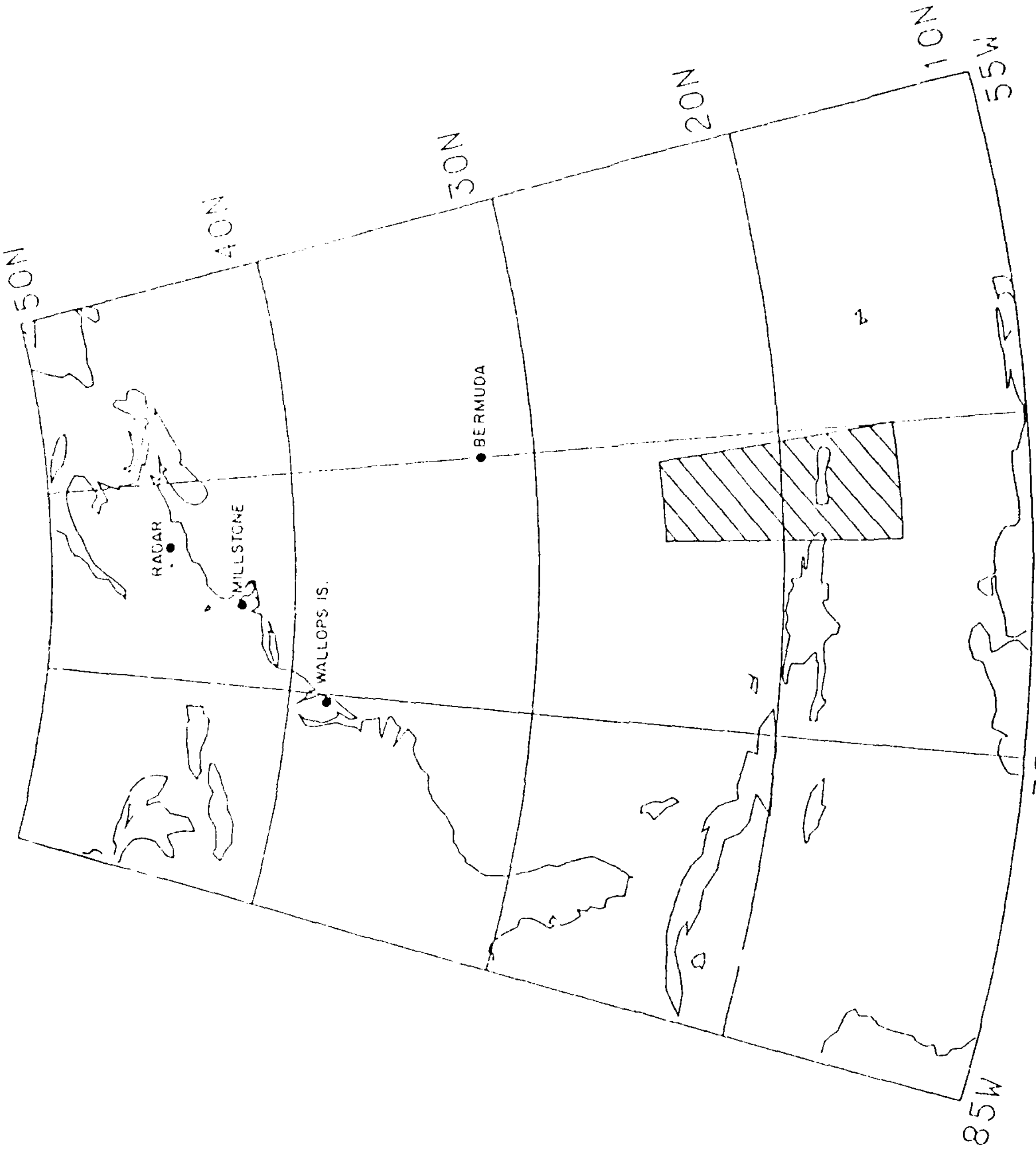

Figure 1. Aircraft Flight Region During the Emulator Test Program

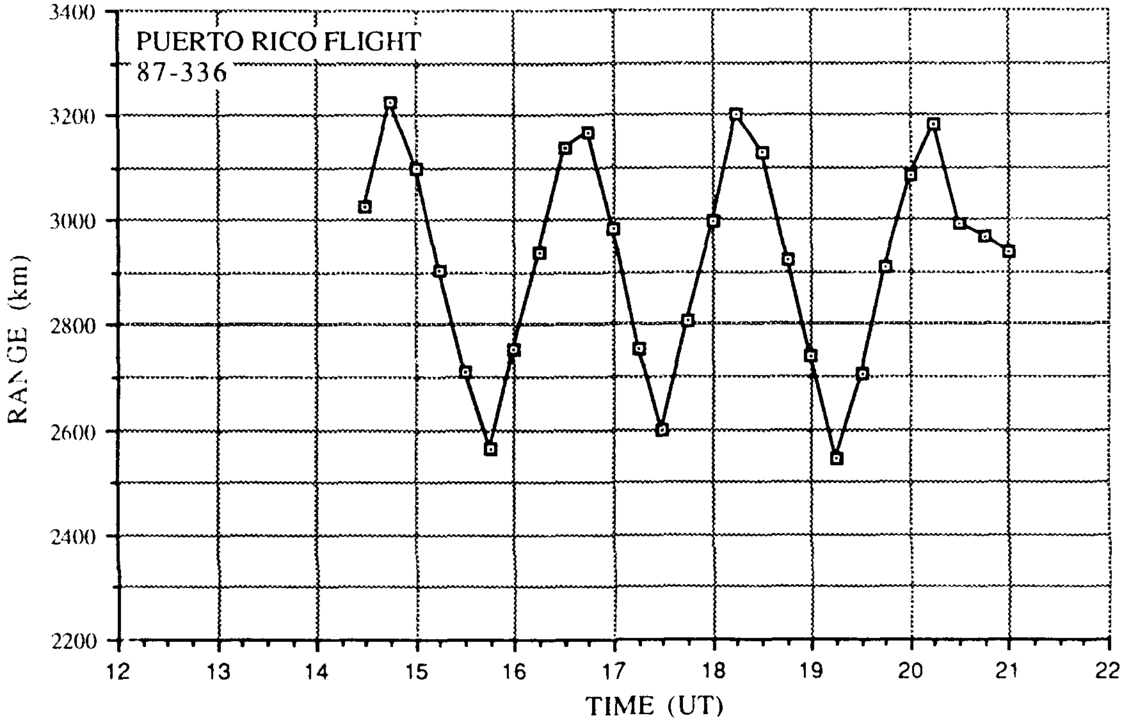

Figure 2. Aircraft Range vs. Time for 87-336

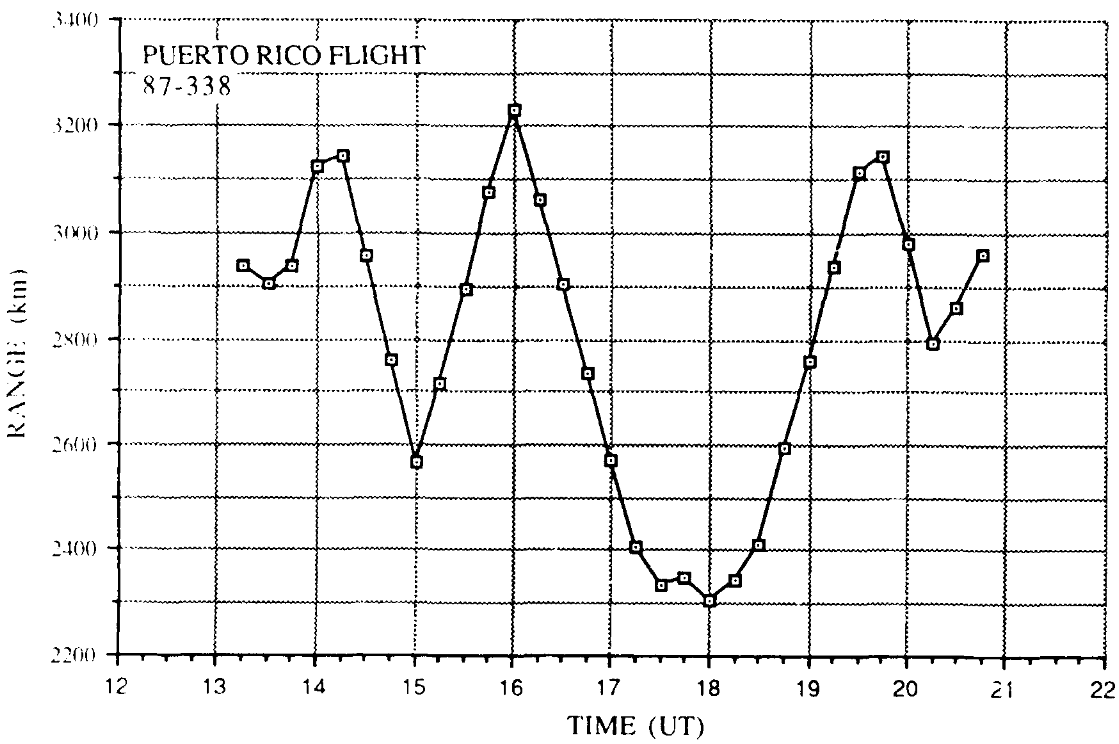

Figure 3. Aircraft Range vs. Time for 87-338

2.0 DATA SCALING

2.1 Vertical Incidence Ionograms

The vertical incidence ionograms made aboard the AIO, at the ULCAR station located at Millstone Hill, MA and at Wallops Island, VA were available for this analysis and these data were scaled in a routine fashion. Future testing in the southern segment of the ECRS should be supported by and coordinated with vertical incidence ionospheric soundings both at Wallops Island and Bermuda. Bermuda actually lies closer (≈ 300 km) to the path midpoint than Wallops Is. (≈ 1000 km) and it would have been preferable to use the Bermuda data for generating the MUF for comparison with the MOF measured on board the AIO. As will be seen later the dominant propagation mode from the radar to the aircraft is the one hop F2 and for this reason this analysis is concentrated on the F2 modes.

Figures 4 and 5 show the time variations of the scaled foF2 measured aboard the AIO for the two flights on 87-336 and 87-338 respectively. Nominally these flights took place during the same time period on both days, that is between 1400 UT and 2000 UT. At the midpoint of the almost north-south path, local noon occurs at 1600 UT well within the flight period. Both flights were similar after 1600 UT in that the foF2 was relatively constant, varying between 6.5 and 9 MHz. On 87-336 prior to 1500 UT the foF2 values as measured on the AIO were running relatively high, around 12 to 13 MHz. The sudden drop of over 5 MHz between 1445 and 1545 UT appears to be unusual and may be related to the location of the equatorial anomaly at the southern end of this leg of the aircraft flight path. It is possible to see, superimposed on this foF2 data, variations that sometimes correlate with the movement of the aircraft. This reflects the usual north-south ionospheric gradients as sensed by the latitudinal changes in the position of the aircraft.

Figure 6 (87-336) and Figure 7 (87-338) show the variations of foF2 as measured at Wallops Is. near the path midpoint. Both days show a

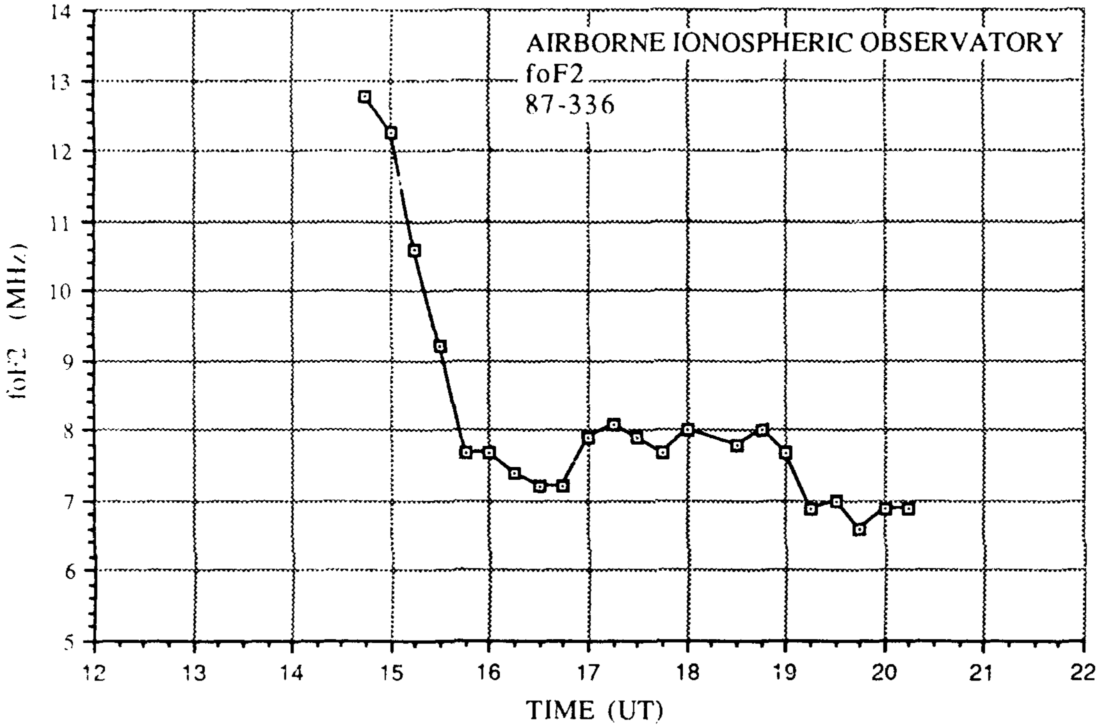

Figure 4. F-Layer Critical Frequency, foF2, Measured Aboard the AIO for 87-336

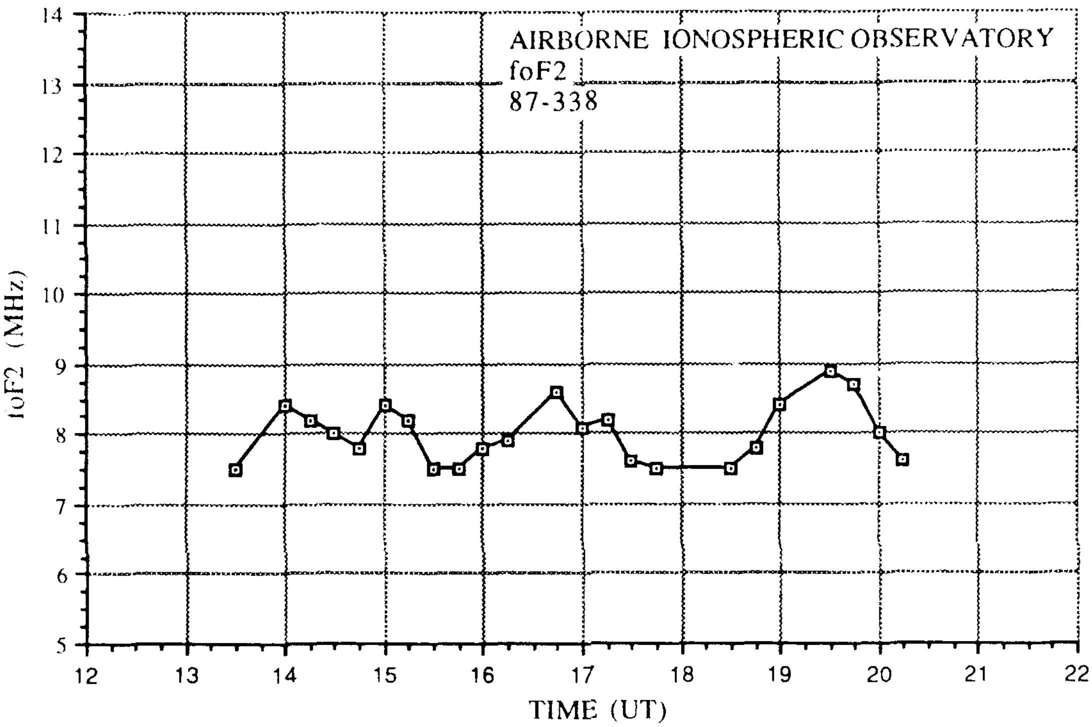

Figure 5. F-Layer Critical Frequency, foF2, Measured Aboard the AIO for 87-338

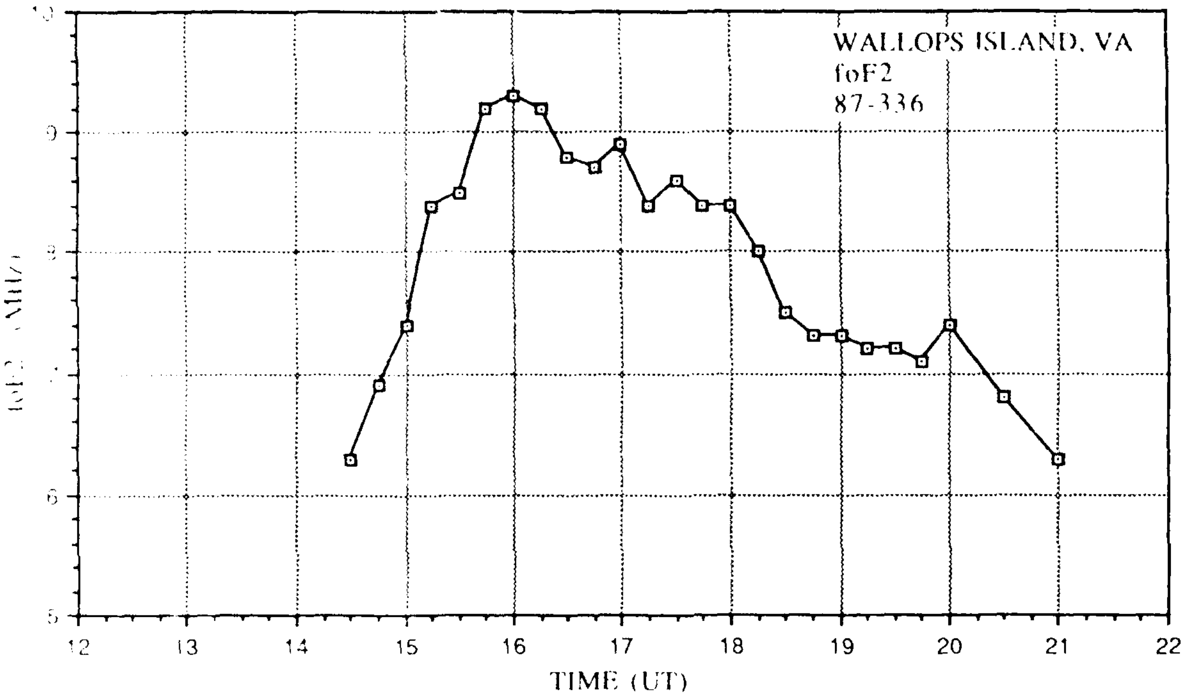

Figure 6 F-Layer Critical Frequency, foF2, Measured at Wallops Is., VA, for 87-336

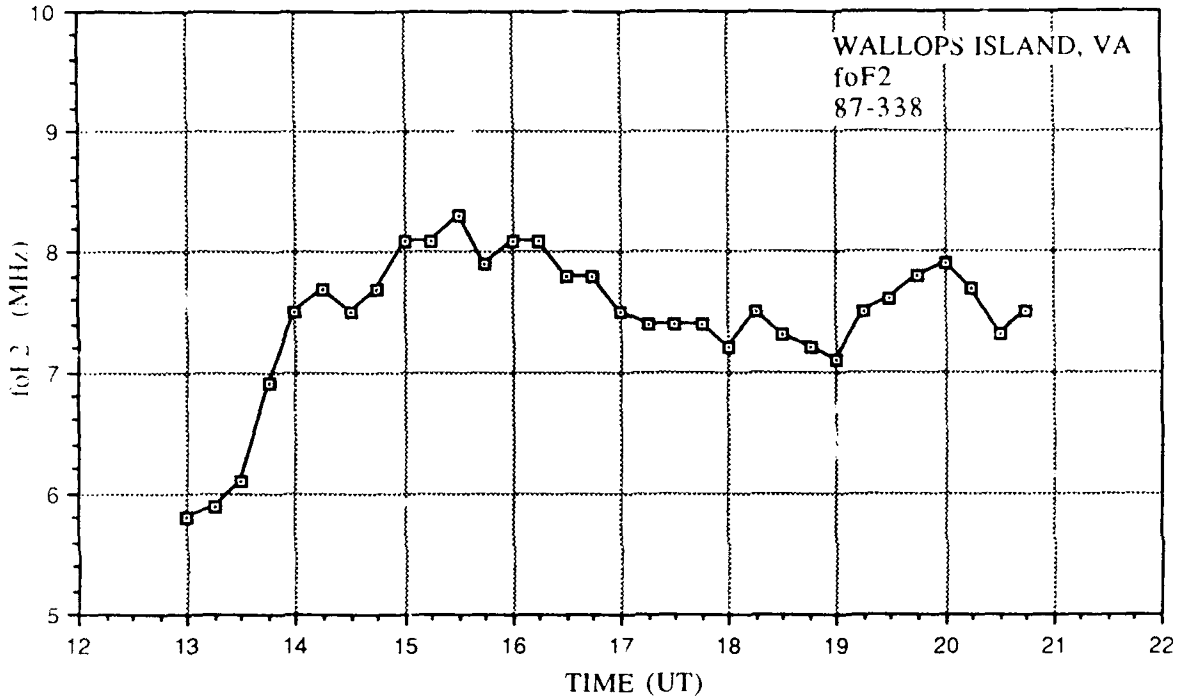

Figure 7. F-Layer Critical Frequency, foF2, Measured at Wallops Is., VA for 87-338

significant increase in foF2 between 1300 and 1500 UT and then a gradual leveling off and finally a slow decrease during the hours past noon.

For completeness, we have included the vertical incidence soundings from Millstone Hill, MA located near the radar end of the propagation path for the same two days (Figures 8 and 9). With these Millstone data it will be possible, with more detailed analysis, to estimate the ionospheric gradients along the propagation path from the radar to the AIO and to assess their effects on the prediction of the MUF using only the midpath data. The comparison of Millstone Hill and Wallops Island foF2 at the same time show significant differences, particularly on 89-336, that illustrate the temporal variability in the north-south gradients.

This part of the study will support future efforts to invert the process, i.e. to use oblique ionograms to determine the local midpath ionosphere.

2.2 Oblique Ionogram Scaled Parameters

For this preliminary report, only the MOF(1F2) and the MOF(2F2) were scaled using the oblique ionograms made onboard the AIO and the results for the MOF(1F2) for both flights are show in Figures 10 and 11.

One problem becomes immediately apparent in these two figures. The oblique sounding system at the radar site used an upper frequency limit of 28 MHz, which for both flights was insufficient to measure the MOF at all times. This deficiency is indicated on these figures whenever a value of 28 MHz is plotted.

As the main part of this preliminary investigation, the vertical ionograms from Wallops Is. were used to determine the predicted MUF by applying transmission curve overlays. These overlays were generated at ULCAR in increments of 200 km, e.g. 2400, 2600, 2800 km, etc. The closest

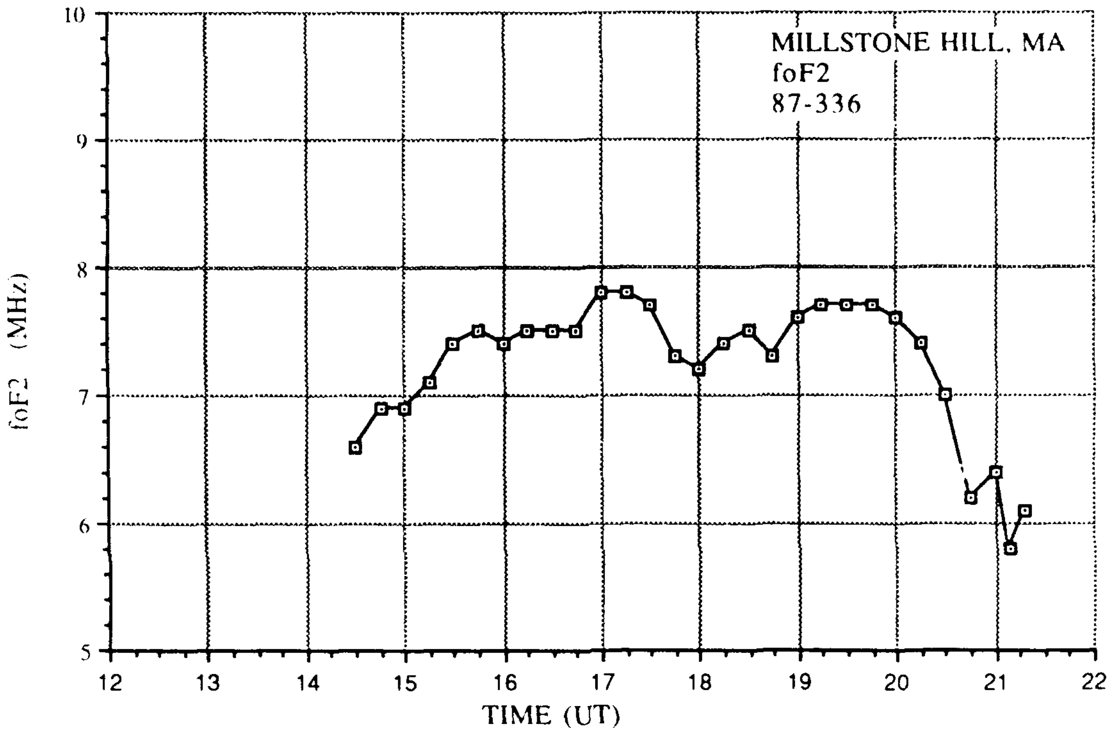

Figure 8. F-Layer Critical Frequency, foF2, Measured at Millstone Hill, MA, for 87-336

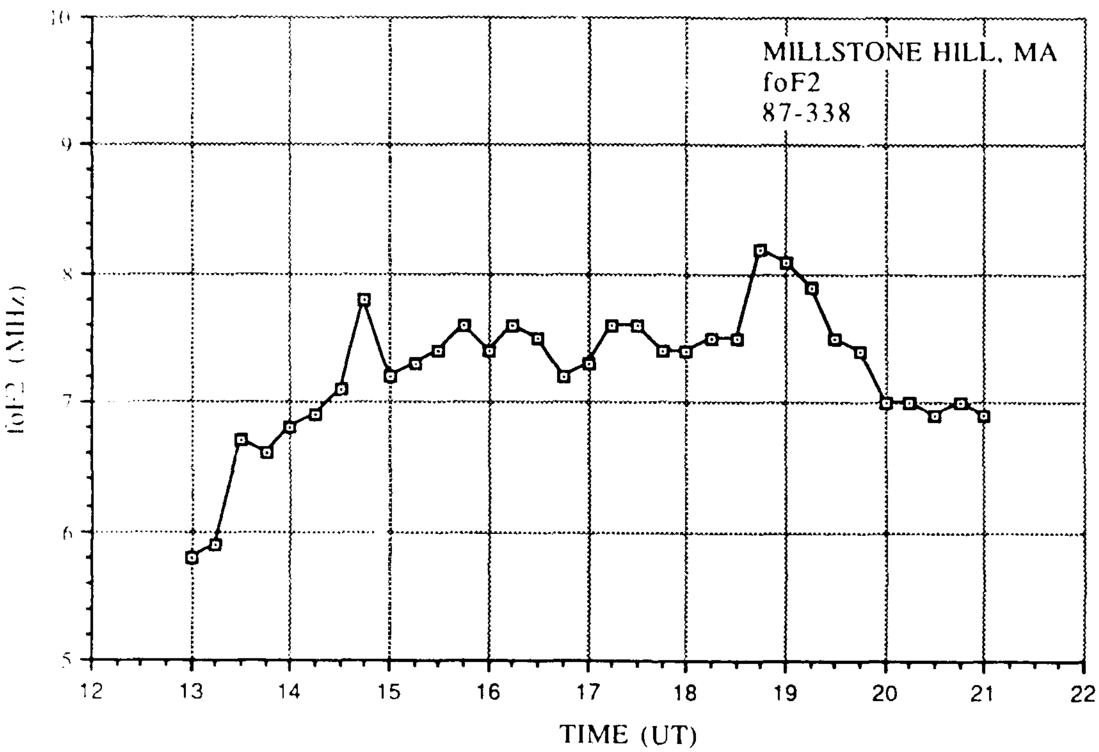

Figure 9. F-Layer Critical Frequency, foF2, Measured at Millstone Hill, MA, for 87-338

overlay to the range of the AIO was selected as the range to the aircraft changes. Then the predicted MUF's values are plotted on the same graphs as the MOF's (Figures 10 and 11).

Although we should not expect a detailed agreement between the two curves because of the distance of Wallops Is., the closest VI sounder (1000 km) to the path midpoint, it is instructive to analyze the differences. The gaps in the MOF curves result from missing oblique ionograms, usually cause by equipment malfunction. Also included here for comparison purposes is the MUF derived by using the same scaling technique for the Millstone Hill VI soundings as for Wallops Island. These results represents what can be expected when an endpath sounder is used for coordinate registration.

Analysis of Differences, 87-336 (Figure 10)

The overlap of all three measurements for this first flight is limited to the time between 1430 UT and 1900 UT. For a good part of this time, the MOF data is limited by the maximum frequency of the radar sounding system as discussed above. After 1730 UT the MOF finally drops below 28 MHz and it is possible to meaningfully compare the measurements. Though, the values of MOF/AIO and Wallops differ during this period by up to 1 MHz, the general trends of the two curves are similar. It is important to remember that there are two major contributors to the time variations of the MUF. Explicit time changes in the ionosphere and aircraft range changes, both of which contribute to the observed variability. Following this brief review of the comparison of these MUF data for the two flights we will examine the relationship between these two factors which contribute to the time variations of the MUF.

Comparing the range change of the AIO from the OTH radar site in Maine as a function of time (Figure 2) with the MUF changes between 1445 UT and 1545 UT, we see that the MUF steadily increases by almost 5 MHz. During this same time the range to the aircraft decreases from 3220 km to 2560 km, opposite to the expected range variation, i.e. opposite to the simple

theory that the maximum useable frequency should decrease with decreasing range. Then after 1545 UT the MUF and the range increase together until 1600 UT when the MUF levels off and then decreases significantly as the AIO range continues to increase. Finally, for the period from 1815 UT to 1930 UT, the MUF and the AIO range changes correlate very well and then after 1930 UT again the two curves move in opposite directions. As we shall see in the next section, the MUF is generally controlled by time variations of the foF2 rather than by the aircraft range changes.

During the time interval from 1500 UT to 1730 UT when the AIO/MOF is at the 28 MHz limit and the Wallops Is. MUF exceeds 28 MHz, the Millstone data shows MUFs between 24 and 26 MHz (Figure 10), well below the 28 MHz limit. This difference is a good illustration of the problems associated with using an endpath sounder to determine propagation conditions.

Analysis of Differences, 87-338 (Figure 11)

Again for this flight, the MUFs scaled from the Wallops Island VI ionograms and the MOFs read directly from the oblique ionograms have very similar variations. Except for short time periods when the MOF is limited during the midday by the 28 MHz upper frequency of the oblique sounder, the differences are remarkably small and can probably be accounted for by the difference between the midpoint critical frequency and the measured value from Wallops Is. For this particular flight there is good correlation between the range changes and the MUF variations except for a short period from 1430 UT to 1500 UT when the MUF goes clearly in the opposite direction to the range change.

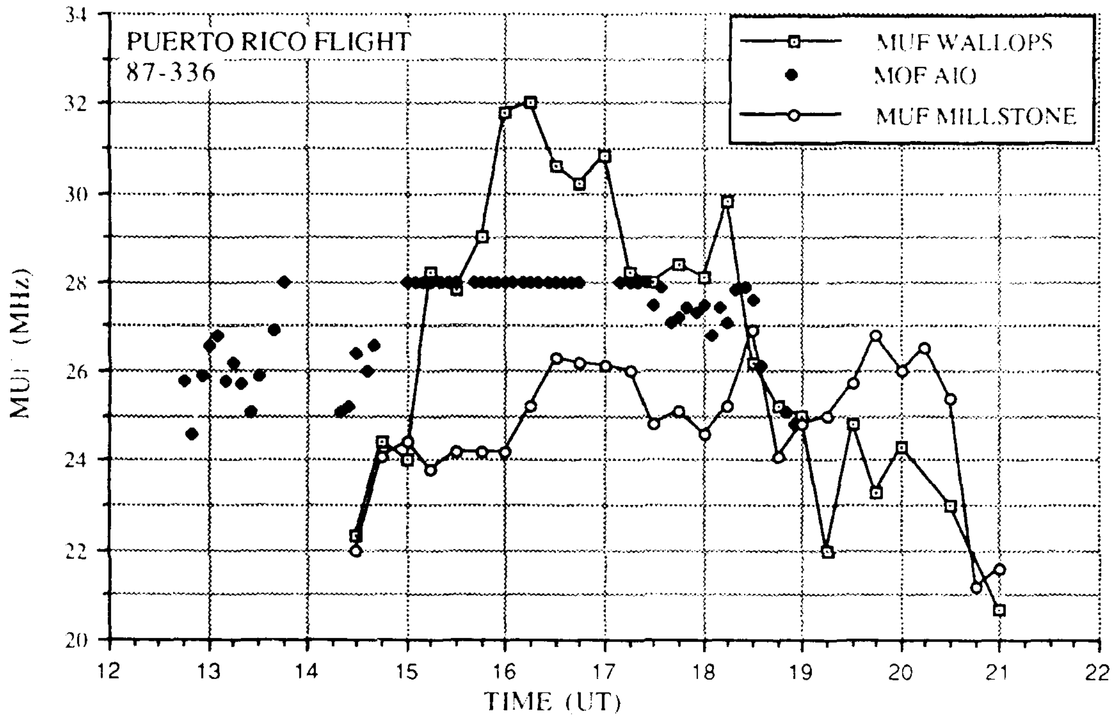

Figure 10. Maximum Observed Frequency and Predicted Maximum Useable Frequency (Wallops Is.) vs. Time During the Flight on 87-336

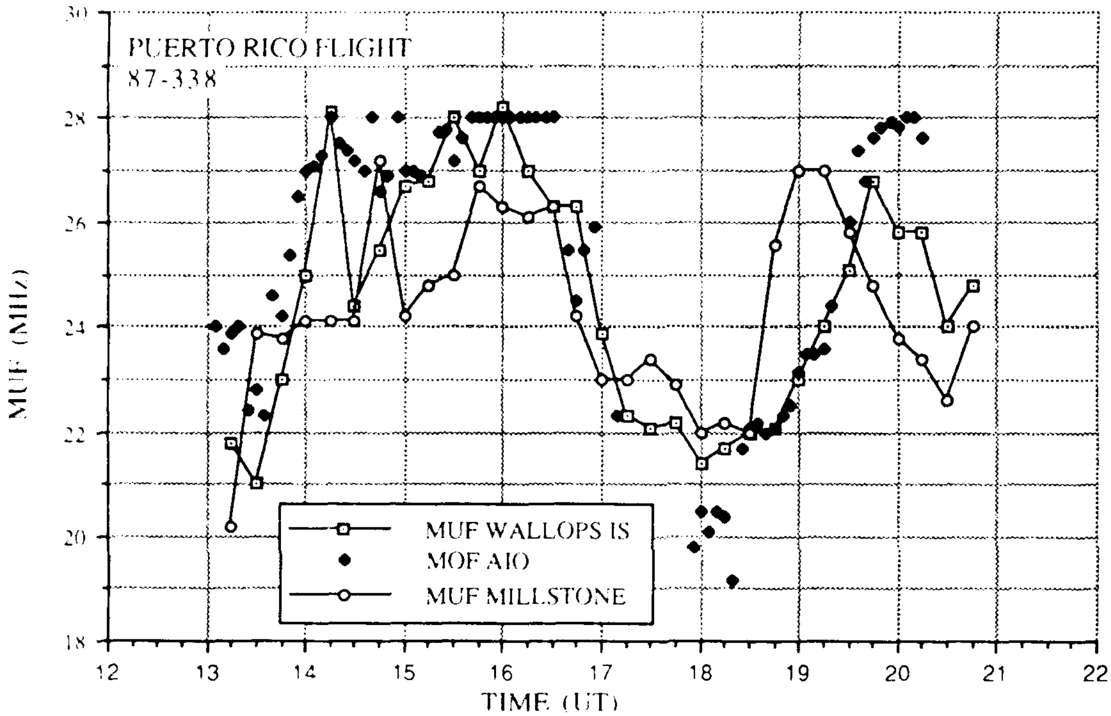

Figure 11. Maximum Observed Frequency and Derived Maximum Useable Frequency (Wallops Is.) vs. Time During the Flight on 87-338

For this flight the latitudinal differences between the MUF values determined at Wallops and at Millstone Hill (a 4.5° latitude difference) are much smaller than for the 87-336 flight. The respective foF2 data also suggest smaller latitudinal foF2 gradients than for 87-336. However there are still substantial differences, of the order of 3 MHz, between the two MUFs, particularly from 1400 UT to 1530 UT and then again between 1830 UT and 1930 UT. For both of these periods the actual AIO/ MOF agrees much better with the near midpath soundings than with the endpath sounding.

3.0 MUF VARIABILITY

In order to better understand the observed changes in the MUF as a function of time, changes which often appear to go in a direction opposite to the changes in the range of the aircraft, it is necessary to investigate the relative contributions to these MUF variations from a) the aircraft motion and b) the explicit time changes in the ionosphere.

Martyn's theorem states that:

$$MUF = f_v \sec(\theta) \qquad (1)$$

In order to simplify this analysis we replace f_v by foF2 in the above expression and then differentiate with respect to time, giving:

$$\frac{d(MUF)}{dt} = \sec\theta \frac{d(foF2)}{dt} + \tan\theta \sec\theta\,(foF2)\frac{d\theta}{dt} \qquad (2)$$

where θ is the angle the ray makes with the local vertical in the ionosphere.

We see that the time variation of the MUF, in this simple model, can be written in terms of the time variation of the layer critical frequency and the time rate of change of the angle θ. The explicit time derivative of the layer critical frequency represents actual time variations as well as a spatial component as the midpath moves under a changing ionosphere with the flight of the aircraft. The second term on the right side of the equation describes the changes in the reflection angle for the oblique path as the aircraft flies towards or away from the radar site.

For a spherical earth using simple geometry, we can write an expression for $\tan\theta$ as:

$$\tan\theta = \frac{\sin\alpha}{\left[\frac{R_e + h}{R_e} - \cos\theta\right]} \tag{3}$$

where α is the half angle at the center of the earth corresponding to the distance between the radar and the aircraft, h is the height of the reflected wave and R_e is the radius of the earth.

Using equation (2), we can evaluate $d\theta/dt$. This is done by differentiating equation (3) with respect to α and then using the relationship:

$$\frac{d\theta}{dt} = \frac{d\theta}{d\alpha} * \frac{d\alpha}{dt}$$

where $\alpha = D/R_e$. Then:

$$\frac{d\theta}{dt} = \frac{d\theta}{d\alpha} \frac{dD}{dt} \frac{1}{R_e} \tag{4}$$

where D is the ground range from the radar to the aircraft.

Differentiating equation (3) we get,

$$\frac{d\theta}{d\alpha} = \frac{\left[\frac{R_e + h}{R_e} \cos\alpha - 1\right]}{\left[\frac{R_e + h}{R_e} - \cos\alpha\right]^2} \tag{5}$$

and then using equation (4) and setting $dD/dt = v_a$ where v_a is the speed of the aircraft, we obtain an expression for $d\theta/dt$. If we assume an ionospheric height of 225 km, an aircraft speed of 200 m/s and foF2 = 8 MHz, the two terms in equation (2) become:

$$\sec\theta \frac{d(foF2)}{dt} = -4.1 \times 10^{3} \ [Hz/sec]$$

and

$$\tan\theta \sec\theta \ (foF2) \frac{d\theta}{dt} = 1.88 \times 10^{2} \ [Hz/sec]$$

where we have selected d(foF2)/dt = -10^3 [Hz/sec] at the time between 1515 UT and 1530 UT on 87-338.

It is clear that under the circumstances of these flights, i.e. at long ranges from the radar, the time dependence of foF2 is more than 20 times greater than the range dependence and of the opposite sign. This indicates that the observed changes in the MUF which often appear uncorrelated with the aircraft range changes are likely caused by temporal changes.

4.0 SUMMARY

For some time the University of Lowell Center for Atmospheric Research has been investigating the effects of horizontal gradients on HF radio wave propagation as part of several OTH radar projects. Current research efforts are directed at developing methods to use single site measurements near the midpath and/or remote sites (some distance from the midpoint of the path) to improve the frequency management procedures by including the effects of gradients into the models. These real-time techniques, using the Digisonde tilt measuring capability in conjunction with the improved model of the gradients, can make significant improvements in radar management. The advantages of a midpath sounder to provide reliable MUF estimates is forcefully illustrated by using both the Wallops Island and the Millstone Hill sounders to compute the expected MOF.

The sensitivity of MUF variations to changes in the ionosphere in the reflection regions show the criticality of these real-time remote measurements and to provide the tools that will permit the radar operators to utilize this information in a timely and effective manner. Continued research in this area will ultimately improve OTH-B radar performance.

Although all systems worked well during these two flights in conjunction with the OTH-B radar emulator studies, without a very concerted effort to coordinate the data gathering at the radar it is difficult to completely evaluate the frequency management procedures. For this preliminary study, it has not been possible to make use of the coordinate registration tables and backscatter ionograms that are available from the radar. A very useful data set would be from the Bermuda VI sounder which lies considerably closer to the midpoint of the propagation path.

Finally, consideration should be given to raising the upper limit of the radar backscatter sounder, particularly when the radar operates in the more southern segments and during periods of high solar activity levels expected during the next few years.